

***Linear Motion Servo Plant: AMD-2***

# ***Active Mass Damper - Two Floors (AMD-2)***



**User Manual**

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## 1. Active Mass Damper – Two-Floor Structure (AMD-2) Presentation

### 1.1. AMD-2: System Description

The typical Active Mass Damper – Two-Floor structure (AMD-2) plant is depicted in Figure 1. The AMD-2 plant is a bench-scale model to emulate a building controlled by an Active Mass Damper (AMD). The plant consists of a two-story building-like structure on top of which a linear cart (i.e. active mass) is driven by a rack and pinion mechanism. The first and second floors are each instrumented with an accelerometer measuring the accelerations of the middle and top floors, respectively, relative to ground. The structure frame is made of steel and is flexible along its facade. Such a scaled structure has been designed to study critical aspects of structural control implementations.

The top (a.k.a. roof) of the structure accommodates a rack and a shaft designed to work with an IP01- or IP02- type of linear cart, which thus constitutes the controllable mass at the top of the structure. The cart is free to move along in the same direction as the structure. Specifically, it is a precisely machined solid aluminum cart which is driven by a high quality DC motor equipped with a planetary gearbox. The cart slides along a stainless steel shaft using linear bearings. When the motor turns, the torque created at the output shaft is translated, through the rack and pinion mechanism, to a linear force (i.e. control force) which results in the cart's motion. The cart position is directly measured using either a potentiometer (for the IP01-based cart) or an encoder (for the IP02-based cart) whose shaft meshes with the track via an additional pinion. Moreover, two masses are available for attachment to

the cart, so that it has more inertia to absorb the structure's vibrations. These two weights can be used or removed for assessing the robustness of the controller and the effects of



Figure 1 AMD-2 System

variations in parameters. For more details regarding the IP01 and IP02 linear servo plants and their applications, please review Reference [1].

Different building/linear cart configurations can be constructed, depending for instance on the location of the cart in the structure. Also several Quanser's single-story AMD buildings can be connected either in series or in parallel. Additionally, the flexible system can also be excited using the Quanser Shake Table II, as described in Reference [2]. Of course, those different combinations allow for Multi-Input-Multi-Output (MIMO) experiments.

### 1.2. AMD-2: Control Challenge

The AMD-2 plant forms an autonomous servo system. The challenge in designing a control system that dampens out the vibrations in the two-story building-like structure is that the deflections of both first and second floors (or horizontal displacement) are NOT measured. Instead, the structure's feedback sensors are two accelerometers mounted on the AMD-2's middle and top floors. The only other sensor that is available is to measure the linear cart position. The only input to the AMD-2 system is the cart motor voltage.

In order to dampen out the vibrations in the AMD-2 flexible structure, the system is supplied with a state-feedback controller based on a full-order observer. The closed-loop control scheme drives the active mass (i.e. linear cart) by taking into account the actual cart position and both floor acceleration feedback signals. Of course, you may design any other controller you wish. The complete mathematical modelling and system parameters are provided to streamline the implementation of the control theory of your choice.

## 2. References

- [1] *IP01 and IP02 User Manual.*
- [2] *Shake Table II Experiment Manual.*

### 3. AMD-2 System Description

#### 3.1. Component Nomenclature

As a quick nomenclature, Table 1, below, provides a list of all the principal elements composing the Active Mass Damper – Two-Floor system (AMD-2). Every element is located and identified, through a unique identification (ID) number, on the AMD-2 plant represented in Figures 2, 3, 4, and 5, below.

<i>ID #</i>	<i>Description</i>	<i>ID #</i>	<i>Description</i>
<b>1</b>	AMD Cart	<b>2</b>	Stainless Steel Shaft
<b>3</b>	Track	<b>4</b>	Linear Bearing
<b>5</b>	Rack End Plate	<b>6</b>	Rack Set Screw: (7/64)"
<b>7</b>	Cart Load Weight	<b>8</b>	Cart Load Weight Set Screw: (3/32)"
<b>9</b>	Cart DC Motor	<b>10</b>	Cart Encoder
<b>11</b>	Cart Motor Pinion	<b>12</b>	Cart Position Pinion
<b>13</b>	Cart Motor Pinion Shaft	<b>14</b>	Cart Position Pinion Shaft
<b>15</b>	Cart Motor Connector	<b>16</b>	Cart Encoder Connector
<b>17</b>	Cart Planetary Gearbox	<b>18</b>	First Floor Flexible Structure
<b>19</b>	Second Floor Flexible Structure	<b>20</b>	Ground Floor
<b>21</b>	First Floor	<b>22</b>	Second Floor
<b>23</b>	First Floor Accelerometer	<b>24</b>	First Floor Accelerometer Connector
<b>25</b>	Second Floor Accelerometer	<b>26</b>	Second Floor Accelerometer Connector
<b>27</b>	Accelerometer Offset Potentiometer	<b>28</b>	Accelerometer Gain Potentiometer

Table 1 AMD-2 Component Nomenclature

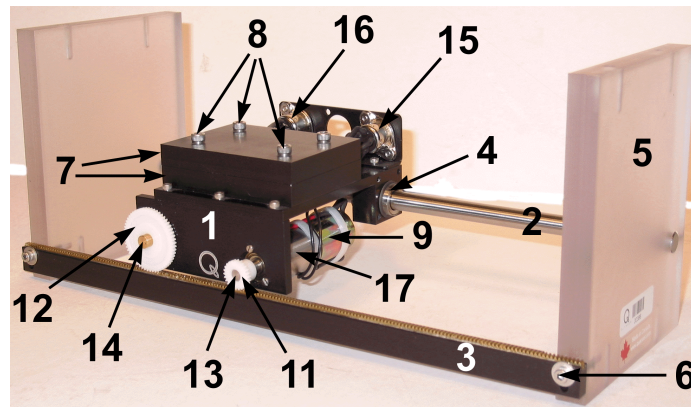


Figure 2 AMD-2 Cart: Front View



Figure 3 AMD-2 Structure: Front View

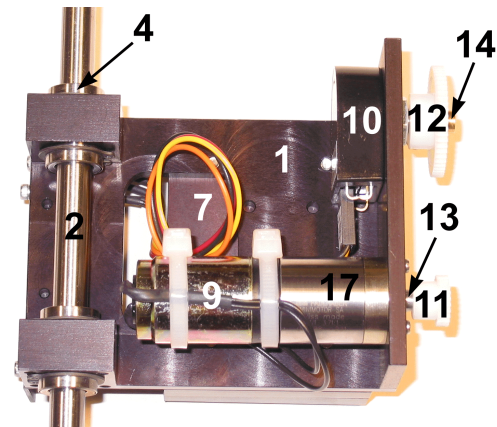


Figure 4 AMD-2 IP02-Type Cart: Bottom View

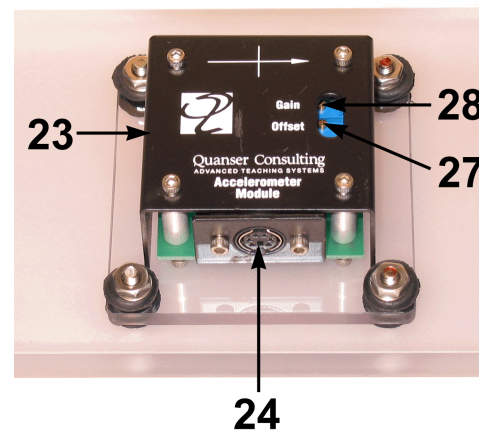


Figure 5 AMD-2 Accelerometer: Bottom View



## 3.2. Component Description

### 3.2.1. Flexible Structure (Components #18 And #19)

The Active Mass Damper – Two-Floor (AMD-2) structure is made of two identical single-story modules connected on top of each other (i.e. in series). Each single-story structural module consists of two vertical steel beams. Each steel column has a section of 1.75 by 108.1 millimeters and a mass of 0.240 kilograms. Each single-story frame external dimensions are shown in Table 2, below.

<i>Description</i>	<i>Value</i>	<i>Unit</i>
Flexible Module Height	0.50	m
Flexible Module Length	0.32	m
Flexible Module Depth	0.11	m

Table 2 Single-Story Module Dimensions

The resulting overall dimensions for the AMD-2 structure are shown in Table 3, below.

<i>Description</i>	<i>Value</i>	<i>Unit</i>
AMD-2 Structure Height	1.00	m
AMD-2 Structure Length	0.32	m
AMD-2 Structure Depth	0.11	m

Table 3 AMD-2 Overall Dimensions

### 3.2.2. Cart Rack (Components #2, #3, and #5)

Table 4, below, characterizes the overall dimensions of the cart rack used in the Active Mass Damper – Two-Floor (AMD-2) system.

<i>Description</i>	<i>Value</i>	<i>Unit</i>
Overall Cart Rack Length	0.31	m
Overall Cart Rack Height	0.13	m
Overall Cart Rack Depth	0.11	m

Table 4 AMD-2 Cart Rack Overall Dimensions

### 3.2.3. Floor Accelerometers (Components # 23 And #25)

Each floor of the building-like structure is equipped with a capacitive DC accelerometer with full-scale range of  $\pm 5$  g. It consists of a single-chip accelerometer with signal conditioning. The AMD-2 accelerometers are calibrated in-house to generate 1 Volt per  $9.81 \text{ m/s}^2$  (i.e. 1 V/g), as characterized by the accelerometer sensitivity shown in Table 5, on page 10.

The accelerometer has the capability to measure both AC/dynamic accelerations (e.g. vibrations) and DC/static accelerations (e.g. gravity). The arrow represented on the accelerometer, and depicted in Figure 5, shows the positive direction of the AC acceleration sensor measurement on its axis of sensitivity. To best measure the AMD-2 floor vibration, both accelerometers are mounted such their sensitive axes are longitudinal to the structure. Quickly pushing each floor of the AMD-2 plant towards the right, when facing the structure, should result in an initial positive acceleration voltage.

Although both AMD-2 accelerometers have already been calibrated at the factory, the signal conditioning circuit properties may vary depending on the external conditions (e.g. humidity, temperature). Therefore, you may want to adjust each accelerometer's *Offset* potentiometer (shown as component #27 in Figure 5) such that it reads approximately zero Volts with zero acceleration (i.e. sensor resting flat or horizontal). Likewise, each accelerometer's *Gain* potentiometer (shown as component #28 in Figure 5) can be adjusted to read minus one Volts when the sensor is resting vertically on its right side with the arrow pointing downwards.

### 3.2.4. Cart DC Motor (Component #9)

The AMD-2 cart incorporates a **Faulhaber Coreless DC Motor (2338S006)**, as represented in Figures 2 and 4 by component #9. This model is a high efficiency low inductance motor resulting in a much faster response than a conventional DC motor. The complete specification sheet of the motor is included in Appendix A.



#### CAUTION:

High Frequency signals applied to a motor will eventually damage the gearbox and/or the motor brushes. The most likely source for high frequency noise is derivative feedback. If the derivative gain is too high, a noisy voltage will be fed into the motor. To protect your motor, you should always band limit your signal (especially derivative feedback) to a value of **50Hz**.



### 3.2.5. Cart Planetary Gearbox (Component #17)

The AMD-2 cart DC motor is coupled to a Faulhaber Planetary Gearhead Series 23/1, as represented in Figures 2 and 4 by component #17. Its reduction ratio is 3.71:1. The complete specification sheet of the planetary gearbox is included in Appendix B.

### 3.2.6. IP01-Based Cart Potentiometer

If the AMD-2 cart is based on the IP01 cart, described in Reference [1], its linear position is sensed by a 10-turn black potentiometer, namely the Vishay Spectrol model 534-1-1-103. The cart potentiometer is connected to a  $\pm 12$  Volt DC power supply through two bias resistors of 7.15 k $\Omega$  each. The total output range of the cart position potentiometer results to be  $\pm 5$ V over its 10 complete turns (i.e. 3600 degrees). The main specifications of the IP01-based AMD-2 cart potentiometer are included in Appendix C.

Refer to Table 5, on page 10, for the resulting potentiometer sensitivity. Pushing manually the AMD-2 cart towards the right side of the track, when facing it, should result in a positive change in the cart position potentiometer voltage. Likewise, pushing the cart towards the left side of the track, when facing it, should result in a decreasing cart position potentiometer voltage.

### 3.2.7. IP02-Based Cart Encoder (Component #10)

If the AMD-2 cart is based on the IP02 cart, described in Reference [1], its linear position is measured with one optical encoder, which is represented in Figure 4 by component #10. The encoder model used in the AMD-2 cart is a US Digital S1 single-ended optical shaft encoder. It offers a high resolution of 4096 counts per revolution (i.e. 1024 lines per revolution with two channels in quadrature).

The complete specification sheet of the S1 optical shaft encoder is included in Appendix D. The internal wiring diagram of the cart encoder is depicted in Figure 6. The standard 5-pin DIN connector, shown in Figure 6, is also pictured as component #16 in Figure 2.

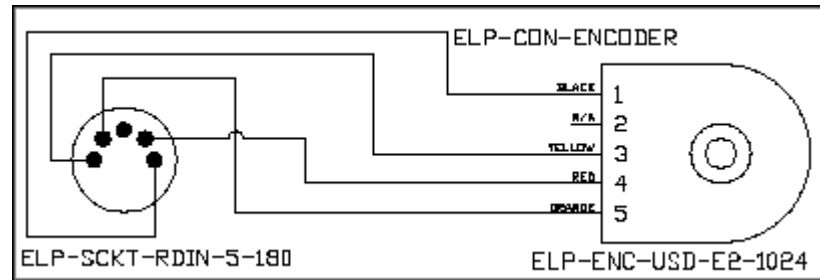


Figure 6 Cart Encoder Wiring

Refer to Table 5, on page 10, for the resulting encoder resolution. Pushing manually the AMD-2 cart towards the right side of the track, when facing it, should result in a positive change in the cart position. Likewise, pushing the cart towards the left side of the track, when facing it, should result in a decreasing cart position.

## 4. AMD-2 Model Parameters

Table 5, below, lists and characterizes the main parameters (e.g. mechanical and electrical specifications, conversion factors) associated with the Active Mass Damper – Two-Floor (AMD-2) plant. Some of these parameters can be used for mathematical modelling of the AMD-2 system as well as to obtain the structure-plus-cart's Equations Of Motion (EOM).

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$H_{f1}$	First Floor Height	0.502	m
$H_{f2}$	Second (i.e. Top) Floor Height	1.035	m
$M_s$	Structure Total Mass (With No Rack And No Cart)	3.300	kg
$M_{f1}$	First Floor Mass	1.160	kg
$M_{f2}$	Second Floor Mass (With Rack)	1.380	kg
$M_r$	Rack Mass	0.700	kg
$M_c$	Cart Mass (With Two Weights)	0.650	kg
$M_w$	Cart Weight Mass	0.130	kg
$K_{f1}$	First Floor Linear Stiffness Constant (Relative To The Ground)	500	N/m
$K_{f2}$	Second Floor Linear Stiffness Constant (Relative To The First Floor)	500	N/m
$T_c$	Cart Travel (i.e. Stroke)	0.19	m
$P_r$	Rack Pitch	1.664E-003	m/tooth
$V_{nom}$	Cart Motor Nominal Input Voltage	6.0	V
$f_{v_{max}}$	Cart Motor Input Voltage Maximum Frequency	50	Hz
$R_m$	Cart Motor Armature Resistance	2.6	$\Omega$
$L_m$	Cart Motor Armature Inductance	0.18	mH
$K_t$	Cart Motor Torque Constant	0.00767	N.m/A
$\eta_m$	Cart Motor Efficiency	100	%
$K_m$	Cart Back-ElectroMotive-Force (EMF) Constant	0.00767	V.s/rad
$J_m$	Cart Rotor Moment of Inertia	3.90E-007	kg.m <sup>2</sup>

<i>Symbol</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>
$B_{eq}$	Equivalent Viscous Damping Coefficient, as seen at the Motor Pinion	3.0	N.s/m
$K_g$	Cart Planetary Gearbox Gear Ratio	3.71	
$\eta_g$	Cart Planetary Gearbox Efficiency	100	%
$r_{mp}$	Cart Motor Pinion Radius	6.35E-003	m
$N_{mp}$	Cart Motor Pinion Number of Teeth	24	
$r_{pp}$	Cart Position Pinion Radius	1.48E-002	m
$N_{pp}$	Cart Position Pinion Number of Teeth	56	
$K_{EC}$	Cart Encoder Resolution (if IP02-Based)	2.275E-005	m/count
$K_{PC}$	Cart Potentiometer Sensitivity (if IP01-Based)	0.0931	m/V
$K_{ACC}$	Floor Accelerometer Sensitivity	9.81	m/s <sup>2</sup> /V

Table 5 AMD-2 System Parameters

## 5. Wiring Procedure For The AMD-2 System

This section describes the standard wiring procedure for the Active Mass Damper – Two-Floor (AMD-2) plant.

The following hardware, accompanying the AMD-2, is assumed:

- Power Amplifier: Quanser UPM 1503 / UPM 2405 or equivalent.
- Data Acquisition Card: Quanser Q8 / MultiQ-PCI / MultiQ-3, or one of the National Instruments E-Series cards, or equivalent.

### 5.1. Cable Nomenclature

Table 6, below, provides a description of the standard cables used in the wiring of the AMD-2.



<i>Cable</i>	<i>Designation</i>	<i>Description</i>
	5-pin-DIN to RCA	This cable connects an analog output of the data acquisition terminal board to the power module for proper power amplification.
	4-pin-DIN to 6-pin-DIN	This cable connects the output of the power module, after amplification, to the desired actuator (e.g. cart motor). One end of this cable contains a resistor that sets the amplification gain (e.g. 1, 3, 5).

Figure 7 "From Digital-To-Analog" Cable

Figure 8 "To Load" Cable Of Gain 1

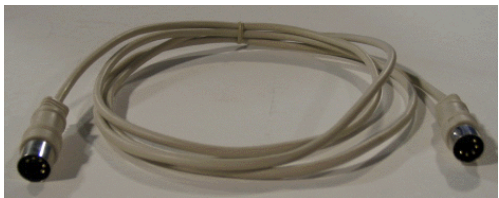
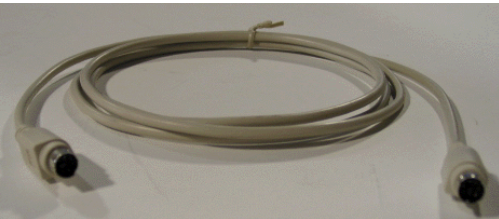
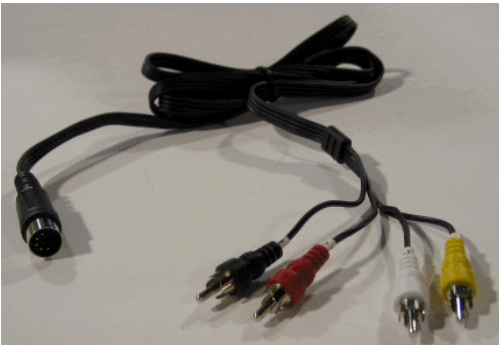
<i>Cable</i>	<i>Designation</i>	<i>Description</i>
 <p>Figure 9 "Encoder" Cable</p>	5-pin-stereo-DIN to 5-pin-stereo-DIN	<p>This cable carries the encoder signals between the encoder connector and the data acquisition board (to the encoder counter). Namely, these signals are: +5VDC power supply, ground, channel A, and channel B.</p>
 <p>Figure 10 "From Analog Sensors" Cable</p>	6-pin-mini-DIN to 6-pin-mini-DIN	<p>This cable carries analog signals from one or two plant sensors (e.g. floor accelerometer, cart potentiometer) to the UPM, where the signals can be either monitored and/or used by an analog controller. The cable also carries a <math>\pm 12</math>VDC line from the UPM in order to power a sensor and/or signal conditioning circuitry.</p>
 <p>Figure 11 "To Analog-To-Digital" Cable</p>	5-pin-DIN to 4xRCA	<p>This cable carries the analog signals, previously taken from the plant sensors (e.g. floor accelerometer, cart potentiometer), unchanged, from the UPM to the Digital-To-Analog input channels on the data acquisition terminal board.</p>

Table 6 Cable Nomenclature

The connectors are also fully compatible with our quick-connect system enabling you to switch from one experiment to another quickly and efficiently.



## 5.2. Hardware Requirements

Figures 12, 13, 14, and 15, below, show, respectively, the top of the AMD-2, the Q8 Terminal Board, the bottom of the AMD-2 system, and the Universal Power Module (e.g. UPM1503), all connected with the necessary cabling to interface to and use the AMD-2 plant.

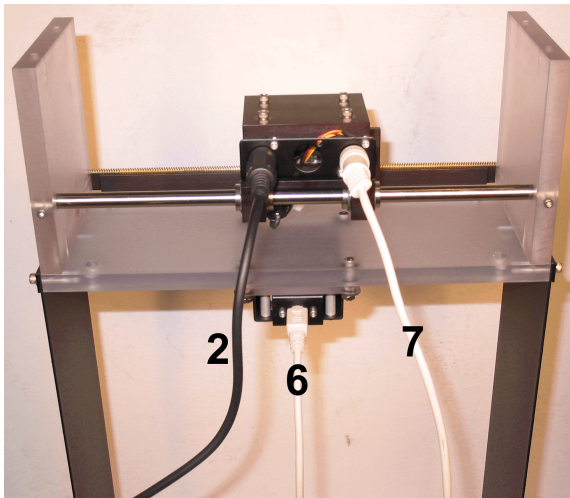


Figure 12 AMD-2 Top Connections

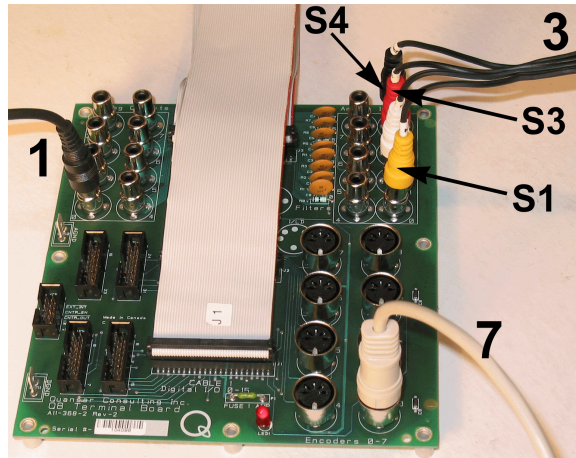


Figure 13 Q8 Terminal Board Connections

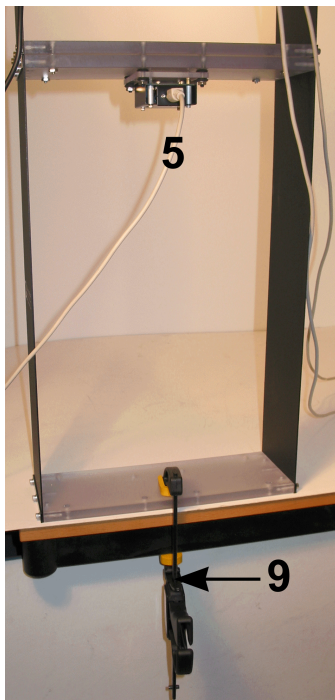


Figure 14 AMD-2 Bottom Connections

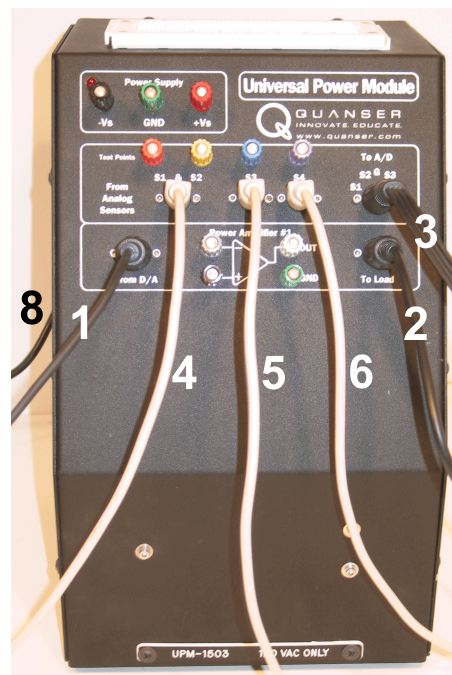


Figure 15 Universal Power Module: UPM1503

Together with the power supply for the amplifier, all Quanser power modules are equipped with a 1-ampere  $\pm 12$ -volt regulated DC power supply for signal conditioning of external analog sensors.

## 5.3. Typical Connections For The AMD-2 System

### 5.3.1. Wiring Of The Cart DC Motor Power Line

The "power" line wiring of the AMD-2 cart DC motor consists of two connections, as described below:

1. **Connect the "From Digital-To-Analog" Cable – Cable #1:**

The "From Digital-To-Analog" cable is the 5-pin-DIN-to-RCA cable described in Table 6 and shown in Figure 7. Connect the RCA end of this cable to the **Analog Output 0** (i.e. DAC # 0) of your data acquisition card terminal board and its 5-pin-DIN connector to the socket labelled **"From D/A"** on the Quanser Universal Power Module (UPM). These two connections are illustrated by cable #1 in Figures 13 and 15, above.

2. **Connect the "To Load" Cable Of Gain 1 – Cable #2:**

The "To Load" cable of gain 1 is the 4-pin-DIN-to-6-pin-DIN cable described in Table 6 and shown in Figure 8. First, connect the cable 4-pin-DIN connector to the AMD-2 cart **Motor Connector**, which is shown as component #15 in Figure 2. Then connect the cable 6-pin-DIN connector to the UPM socket labelled **"To Load"**. These two connections are illustrated by cable #2 in Figures 12 and 15, above.

### 5.3.2. Wiring Of The Feedback Signals

The AMD-2 system provides three feedback signals. First, the linear cart position signal is produced using either a potentiometer, if the cart is based on the IP01, or an encoder, if the cart is based on the IP02. Second and last, the acceleration signals of the structure first and second floors are provided by using an accelerometer on each floor. To connect these feedback sensors, follow the steps described below:

1. **Connect the "From Analog Sensors" Position Cable – Cable #4:**

In case of an IP01-based cart, the position potentiometer has to be connected. The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 6 and shown in Figure 10. First connect one end of the cable to the IP01-based cart's **S1 & S2 Connector**, as shown in Reference [1]. Then connect the cable's other end

to the UPM socket labelled "**S1 & S2**", which is contained inside the UPM "From Analog Sensors" front panel. This connection to the UPM is illustrated by cable #4 in Figure 15, above.

2. **Connect the "Encoder" Position Cable – Cable #7:**

In case of an IP02-based cart, the position encoder has to be connected. The "Encoder" cable is the 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable described in Table 6 and shown in Figure 9. First connect one end of the cable to the IP02-based cart's **Encoder Connector**, which is shown as component #16 in Figure 2. Then connect the cable's other end to the **Encoder Input 0** on your data acquisition card terminal board. These two connections are illustrated by cable #7 in Figures 12 and 13, above.



**CAUTION:**

Any encoder should be directly connected to the Quanser terminal board (or equivalent) using a standard 5-pin DIN cable. **DO NOT connect the encoder cable to the UPM!**

3. **Connect the "From Analog Sensors" First Floor Acceleration Cable – Cable #5:**

The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 6 and shown in Figure 10. First connect one end of the cable to the **First Floor Accelerometer Connector**, which is located at the back of the AMD-2's first floor as shown by component #24 in Figures 3 and 5, above. Then connect the cable's other end to the UPM socket labelled "**S3**", which is contained inside the UPM "From Analog Sensors" front panel. These connections are illustrated by cable #5 in Figures 14 and 15, above.

4. **Connect the "From Analog Sensors" Second Floor Acceleration Cable – Cable #6:**

The "From Analog Sensors" cable is the 6-pin-mini-DIN-to-6-pin-mini-DIN cable described in Table 6 and shown in Figure 10. First connect one end of the cable to the **Second Floor Accelerometer Connector**, which is located at the back of the AMD-2's second floor as shown by component #26 in Figure 3, above. Then connect the cable's other end to the UPM socket labelled "**S4**", which is contained inside the UPM "From Analog Sensors" front panel. These connections are illustrated by cable #6 in Figures 12 and 15, above.

5. **Connect the "To Analog-To-Digital" Cable – Cable #3:**

The "To Analog-To-Digital" cable is the 5-pin-DIN-to-4xRCA cable described in Table 6 and shown in Figure 11. First, connect the cable 5-pin-DIN connector to the UPM socket labelled "**To A/D**", as illustrated by cable #3 in Figure 15, above. The other end of the cable is split into four RCA connectors, each one labelled with a single digit ranging from one to four. This numbering corresponds to the four possible analog sensor signals passing through the UPM, namely S1, S2, S3 and S4. In order for the analog

signals to be used in software, you should then connect all four RCA connectors to the first four analog input channels of your data acquisition card terminal board. Specifically, connect **S1 to Analog Input 0**, **S2 to Analog Input 1**, **S3 to Analog Input 2**, and **S4 to Analog Input 3**, as illustrated by cable #3 in Figure 13, above.

In other words, the AMD-2 cart position is either sensed using A/D #0 through the UPM analog channel S1 if the cart has a potentiometer (i.e. based on the IP01), or using Encoder Channel #0 if the cart has an encoder (i.e. based on the IP02). The flexible structure top floor's acceleration is measured using A/D #3 through the UPM analog channel S4.

### 5.3.3. AMD-2 Wiring Summary

Table 7, below, sums up the electrical connections necessary to run the AMD-2 system.

<i>Cable #</i>	<i>From</i>	<i>To</i>	<i>Signal</i>
1	DAC #0	UPM "From D/A"	Control signal to the UPM.
2	UPM "To Load"	AMD-2 "Motor Connector"	Power leads to the cart DC motor.
3	UPM "To A/D"	Terminal Board: S1 to ADC #0 S3 to ADC #2 S4 to ADC #3	IP01-based cart potentiometer, if present, and both accelerometer signals to the data acquisition terminal board, through the UPM.
4	AMD-2 Cart "S1 & S2 Connector"	UPM "S1 & S2"	IP01-based cart position feedback signal, if necessary, to the UPM.
5	AMD-2 First Floor "Accelerometer Connector"	UPM "S3"	First floor accelerometer feedback signal to the UPM.
6	AMD-2 Second Floor "Accelerometer Connector"	UPM "S4"	Second floor accelerometer feedback signal to the UPM.
7	AMD-2 Cart "Encoder Connector"	Terminal Board: Encoder Channel #0	IP02-based cart position feedback signal, if necessary, to the data acquisition card.

<i>Cable #</i>	<i>From</i>	<i>To</i>	<i>Signal</i>
8	Power Supply Outlet	UPM Power Socket	UPM Power Supply.

Table 7 AMD-2 Wiring Summary

## 6. Setting Up the AMD-2 Plant

For safety and proper operation, the AMD-2 base plate (a.k.a. "ground" floor) should be rigidly clamped or screwed down to a table or workbench. As an example, a C-clamp is depicted in Figure 14, above, as represented by component #9.

## 7. Obtaining Support

**Note that a support contract may be required to obtain technical support.** To obtain support from Quanser, go to <http://www.quanser.com> and click on the *Tech Support* link. Fill in the form with all requested software version and hardware information and a description of the problem encountered. Submit the form. Be sure to include your email address and a telephone number where you can be reached. A qualified technical support person will contact you.



		2338 S	4.5 S	006 S	009 S	012 S	018 S	024 S					
1	Nominal voltage	$U_N$	4.5	6	9	12	18	24	Volt				
2	Terminal resistance	$R \pm 12\%$	1.4	2.6	5.7	10.0	23.5	38.0	$\Omega$				
3	Output power	$P_2 \text{ max.}$	3.39	3.23	3.29	3.31	3.18	3.50	W				
4	Efficiency	$\eta \text{ max.}$	70	69	67	66	67	67	%				
5	No-load speed	$n_0 \pm 12\%$	7,200	7,200	7,400	7,800	7,400	7,600	rpm				
6	No-load current (with shaft $\varnothing$ 0.12 in)	$I_0 \pm 50\%$	0.100	0.080	0.060	0.050	0.030	0.025	A				
7	Stall torque	$M_H$	2.55	2.42	2.41	2.29	2.32	2.49	oz-in				
8	Friction torque	$M_R$	0.082	0.086	0.095	0.099	0.095	0.102	oz-in				
9	Speed constant	$k_n$	1,650	1,240	855	678	428	330	rpm/V				
10	Back-EMF constant	$k_E$	0.606	0.804	1.170	1.470	2.340	3.030	mV/rpm				
11	Torque constant	$k_M$	0.818	1.088	1.586	1.997	3.158	4.107	oz-in/A				
12	Current constant	$k_i$	1.222	0.919	0.630	0.501	0.317	0.244	A/oz-in				
13	Slope of n-M curve	$\Delta n/\Delta M$	2,824	2,975	3,071	3,406	3,190	3,052	rpm/oz-in				
14	Rotor inductance	$L$	100	180	380	630	1,400	2,600	$\mu H$				
15	Mechanical time constant	$\tau_m$	20	17	17	17	17	17	ms				
16	Rotor inertia	$J$	$6.797 \cdot 10^{-5}$	$5.523 \cdot 10^{-5}$	$5.240 \cdot 10^{-5}$	$4.815 \cdot 10^{-5}$	$5.098 \cdot 10^{-5}$	$5.381 \cdot 10^{-5}$	oz-in-sec <sup>2</sup>				
17	Angular acceleration	$\alpha \text{ max.}$	38	44	46	48	46	47	$10^3 \text{ rad/s}^2$				
18	Thermal resistance	$R_{th1} / R_{th2}$	3 / 24						$^{\circ}C/W$				
19	Thermal time constant	$\tau_{w1} / \tau_{w2}$	5.7 / 645						s				
20	Operating temperature range:								$^{\circ}C$ ( $^{\circ}F$ )				
	– motor		– 30 to +85 (– 22 to +185)						$^{\circ}C$ ( $^{\circ}F$ )				
	– rotor, max. permissible		+125 (+257)						$^{\circ}C$ ( $^{\circ}F$ )				
	Note: Special operating temperature models for		– 55 $^{\circ}C$ to +125 $^{\circ}C$ (– 67 $^{\circ}F$ to +257 $^{\circ}F$ ) available on request.										
21	Shaft bearings		sintered bronze sleeves		ball bearings (optional)		ball bearings, preloaded (optional)						
22	Shaft load max.:		(standard)		(optional)		(optional)						
	– with shaft diameter		0.1181		0.1181		0.1181		in				
	– radial at 3,000 rpm (0.12 in from bearing)		9		72		72		oz				
	– axial at 3,000 rpm		1.08		7.2		7.2		oz				
	– axial at standstill		72		72		72		oz				
23	Shaft play:												
	– radial	$\leq$	0.0012		0.0006		0.0006		in				
	– axial	$\leq$	0.0079		0.0079		0		in				
24	Housing material		steel, zinc galvanized and passivated										
25	Weight		2.47						oz				
26	Direction of rotation		clockwise, viewed from the front face										
<b>Recommended values</b>													
27	Speed up to	$n_e \text{ max.}$	6,000	6,000	6,000	6,000	6,000	6,000	rpm				
28	Torque up to	$M_e \text{ max.}$	0.566	0.566	0.566	0.566	0.566	0.566	oz-in				
29	Current up to (thermal limits)	$I_e \text{ max.}$	1.380	1.000	0.680	0.510	0.330	0.260	A				





## Appendix B. Cart Planetary Gearhead Specification Sheet

### Series 23/1

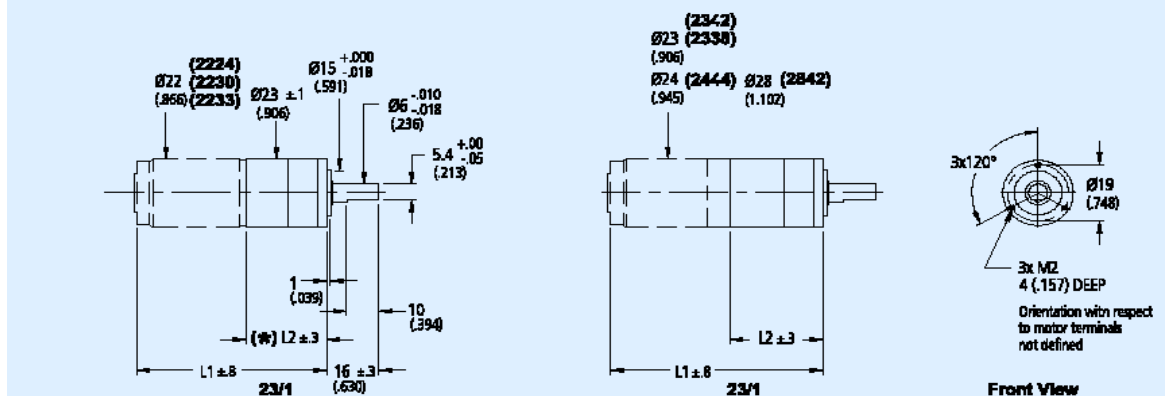
Housing material	23/1 metal
Geartrain material	all steel
Recommended max. input speed for:	
– continuous operation	4,000 rpm
Backlash, at no-load	≤ 1°
Bearings on output shaft	preloaded ball bearings
Shaft load, max.:	
– radial (10 mm (0.394 in) from mounting face)	≤ 612 oz
– axial	≤ 540 oz
Shaft press fit force, max.	≤ 540 oz
Shaft play (on bearing output):	
– radial	≤ 0.0006 in
– axial	= 0.0039 in
Operating temperature range	–30 to +100 °C (– 22 to +212 °F)

Specifications												
reduction ratio (nominal)	weight without motor	length without motor L2	length with motor						output torque		direction of rotation (reversible)	efficiency
			2224 U	2230 U	2233 U	2444 S	2342 S 2842 S	continuous operation	intermittent operation			
			L1	L1	L1 (1)	L1	L1	M max. oz-in	M max. oz-in			
	oz	mm (in)	mm (in)	mm (in)	mm (in)	mm (in)	mm (in)	mm (in)			=	%
3.71 : 1	2.12	23.8 (0.937)	44.1 (1.74)	53.8 (2.12)	56.6 (2.23)	-	-	-	28.32	56.65	=	88
3.71 : 1	2.12	27.8 (1.09)	-	-	-	-	71.8 (2.83)	69.8 (2.75)	28.32	56.65	=	88
14 : 1	2.47	34.1 (1.34)	54.4 (2.14)	60.2 (2.37)	63.0 (2.48)	78.1 (3.07)	76.1 (3.00)	42.48	84.97	=	80	
43 : 1	3.17	40.3 (1.59)	60.6 (2.39)	66.4 (2.61)	69.2 (2.72)	84.3 (3.32)	82.3 (3.24)	99.13	141.6	=	70	
66 : 1	3.17	40.3 (1.59)	60.6 (2.39)	66.4 (2.61)	69.2 (2.72)	84.3 (3.32)	82.3 (3.24)	99.13	141.6	=	70	
134 : 1	3.53	46.4 (1.83)	66.7 (2.63)	72.5 (2.85)	75.3 (2.96)	90.4 (3.56)	88.4 (3.48)	99.13	141.6	=	60	
159 : 1	3.53	46.4 (1.83)	66.7 (2.63)	72.5 (2.85)	75.3 (2.96)	90.4 (3.56)	88.4 (3.48)	99.13	141.6	=	60	
246 : 1	3.53	46.4 (1.83)	66.7 (2.63)	72.5 (2.85)	75.3 (2.96)	90.4 (3.56)	88.4 (3.48)	99.13	141.6	=	60	
415 : 1	3.88	52.6 (2.07)	72.9 (2.87)	78.7 (3.10)	81.5 (3.21)	96.6 (3.80)	94.6 (3.72)	99.13	141.6	=	55	
592 : 1	3.88	52.6 (2.07)	72.9 (2.87)	78.7 (3.10)	81.5 (3.21)	96.6 (3.80)	94.6 (3.72)	99.13	141.6	=	55	
989 : 1	3.88	52.6 (2.07)	72.9 (2.87)	78.7 (3.10)	81.5 (3.21)	96.6 (3.80)	94.6 (3.72)	99.13	141.6	=	55	
1,526 : 1	3.88	52.6 (2.07)	72.9 (2.87)	78.7 (3.10)	81.5 (3.21)	96.6 (3.80)	94.6 (3.72)	99.13	141.6	=	55	

(1) For gearhead length with motor 2338 add 8.7 mm (0.343 in) to 2233 motor length column.

Note: Reduction ratios have been rounded off.  
Exact values are available upon request.

(\*) Subtract 3.9 mm (0.154 in) from L2 column to account for smaller mounting flange.



## Appendix C. IP01-Based Cart Potentiometer Specification Sheet

### 7/8" (22mm) Precision Wirewound Potentiometer



#### FEATURES

- Special Resistance Tolerances to 1%
- Rear Shaft Extensions and Support Bearing
- Non Turn Lug
- Insulating Plastic Shaft
- Special Independent Linearity to  $\pm 0.75\%$
- Dual Gang Configuration and Concentric Shafts
- High Torque and Center Tap
- Special Markings and Front Shaft Extensions
- Servo Unit available and Slipping Clutch

ELECTRICAL SPECIFICATIONS			
PARAMETER	MODEL 533	MODEL 534	MODEL 535
Resistance Range	50 $\Omega$ to 20K $\Omega$	100 $\Omega$ to 100K $\Omega$	50 $\Omega$ to 50K $\Omega$
Standard Values			
Capability Range	5 $\Omega$ to 60K $\Omega$	10 $\Omega$ to 200K $\Omega$	5 $\Omega$ to 100K $\Omega$
Standard Tol	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$
Linearity (Independent)	$\pm 0.25\%$	$\pm 0.25\%$	$\pm 0.25\%$
Noise	100 $\Omega$ ENR	100 $\Omega$ ENR	100 $\Omega$ ENR
Rotation (Electrical & Mechanical)	0° + 10°	0° + 10°	0° + 10°
Power Rating (@ 70°C)	1.0 watts	2.0 watts	1.5 watts
Additional Sections	75% of section 1		
Insulation Resistance	1000M $\Omega$ minimum 500VDC		
Dielectric Strength	1000V <sub>RMS</sub> minimum 60Hz		
Absolute Minimum Resistance	Not to exceed linearity x total resistance or 1 $\Omega$ , whichever is greater		
Tempco	20ppm/°C (standard values, wire only)		
End Voltage	0.25% of total applied voltage, maximum		
Phasing	CCW end points - section 2 phased to section 1 within $\pm 2^\circ$		
Taps	Center tap only		

MARKING		RESISTANCE VALUES	
Unit Identification	Manufacturer's name and model number, resistance value and tolerance, linearity specification date code and terminal identification	Ohms	
		533:	50R, 100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K
		534:	100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K, 50K, 100K
		535:	50R, 100R, 200R, 500R, 1K, 2K, 5K, 10K, 20K, 50K

ORDERING INFORMATION			
The Models 533 (3 turn), 534 (10 turn) and 535 (5 turn) can be ordered by stating			
534	1	2	XXX
MODEL	MOUNTING	NUMBER OF SECTIONS	RESISTANCE EIA CODE SECTION #N
	1. Bushing 2. Servo		(consult factory)

## Appendix D. IP02-Based Cart Encoder Specification Sheet

### S1 & S2

### Optical Shaft Encoders

#### Description:

The **S1** and **S2** series optical shaft encoders are non-contacting rotary to digital converters. Useful for position feedback or manual interface, the encoders convert real-time shaft angle, speed, and direction into TTL-compatible quadrature outputs with or without index. The encoders utilize an unbreakable mylar disk, metal shaft and bushing, LED light source, and monolithic electronics. They may operate from a single +5VDC supply.

The **S1** and **S2** encoders are available with ball bearings for motion control applications or torque-loaded to feel like a potentiometer for front-panel manual interface.

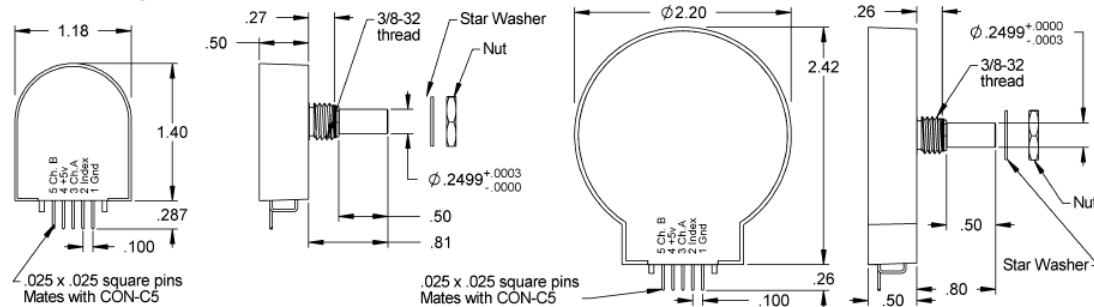
#### Electrical Specifications:

B leads A for clockwise shaft rotation, A leads B for counter clockwise shaft rotation viewed from the shaft/bushing side of the encoder. For complete details see our **HEDS** data sheet.

#### Features:

- Small size
- Low cost
- 2-channel quadrature, TTL square wave outputs
- 3rd channel index option
- Tracks from 0 to 100,000 cycles/sec
- Ball bearing option tracks to 10,000 RPM
- -40 to +100°C operating temperature
- Single +5V supply
- US Digital warrants its products against defects and workmanship for two years. See complete warranty for details.

#### Mechanical Specifications:



#### Mechanical Notes: (ball bearing)

Acceleration	10,000 rad/sec <sup>2</sup>
Vibration	20 g, 5 to 2KHz
Shaft Speed	10,000 RPM max. continuous
Acceleration	50K rad/sec <sup>2</sup>
	10K rad/sec <sup>2</sup> ( <b>S2</b> series)
Shaft Torque	0.05 in. oz. max.
Shaft Loading	1 lb. max.
Bearing Life	(40/P) <sup>3</sup> = Life in millions of revs. P = radial load in pounds.
Weight	0.7 oz.
Shaft Runout	0.0015 T.I.R. max.

#### Mechanical Notes: (sleeve bushing)

Acceleration	10,000 rad/sec <sup>2</sup>
Vibration	20 g, 5 to 2KHz
Shaft Speed	100 RPM max. continuous
Shaft Rotation	Continuous & reversible
Shaft Torque	0.5 ± 0.2 in. oz. 0.3 in. oz. max. ( <b>NT</b> -option)
Shaft Loading	2 lbs. max. dynamic 20 lbs. max. static
Weight	0.7 oz.
Shaft Runout	0.0015 T.I.R. max.

#### Materials & Mounting:

Shaft	Brass or stainless
Bushing	Brass
Connector	Gold plated
Hole Diameter	0.375 in. +0.005 - 0
Panel Thickness	0.125 in. max.
Panel Nut Max Torque	20 in.-lbs.